Interdisciplinary Applications of Autonomous Observation Systems

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LONG-TERM GOALS

Our long-term goal is to develop improved autonomous observation systems and analytical capabilities for describing the distributions and activities of marine microbes in relation to their physical, chemical and optical environment in support of multidisciplinary, data-assimilating predictive models of optical and biological processes in the world ocean.

OBJECTIVES

Our primary objectives are:

- To develop and test new interdisciplinary sensor arrays on a variety of *in situ* platforms to describe biological variability in relation to the optical, physical and chemical environment of the ocean; and

- To use data from these sensor systems in multidisciplinary models of physically and chemically driven ocean biology.

APPROACH

Data from deployments of coastal ocean observatories and research cruises are used to develop and evaluate models and bio-optical algorithms for estimating optical and biological properties of surface waters using measurements from a variety of optical instruments. An extensive program of sampling from research vessels at our coastal observatories provides a large set of data for development and validation of bio-optical models for case 2 waters.

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Several of our bio-optical analyses utilize chlorophyll fluorescence — sun-induced, or stimulated by a variety of fluorometers — to describe variability in the biomass or physiological status of phytoplankton. Consequently, we study the environmental influences on chlorophyll fluorescence in controlled laboratory experiments using different taxonomic groups of phytoplankton. The research employs Satlantic's Fluorescence Induction and Relaxation (FIRe) fluorometer as well as other commercially available fluorometers. We are also working on reconciling spatial and temporal patterns in sun-induced fluorescence yield (assessable from space) with patterns of relative fluorescence yield detected with fluorometers at the surface and in the ocean interior. The objective is to link assessments of phytoplankton physiology from space to autonomous measurements from instruments such as ocean gliders and the physical/biological interactions that they describe.

More broadly, we are working within our own research group and with others in the ocean-observation community to develop effective new ways to make ocean observatory data easily accessible to a broad range of users and to explore new technologies for ocean monitoring.

This work is closely coordinated with the NSERC/Satlantic Industrial Research Chair in Environmental Observation Technology, a partnership between John Cullen (the Chair), Dalhousie University and Satlantic. The Research Chair facilitates a broad range of collaborative research, including coastal observatories in Nova Scotia (see "Related Projects"). This ONR project provides funding for additional support from Satlantic which complements Dalhousie-based efforts.

WORK COMPLETED

Optical moorings and ground-truthing in coastal waters. We summarized the accomplishments of our six-year program of research aimed at developing data-driven, interdisciplinary marine environmental forecasts in coastal waters of Nova Scotia (Cullen et al. 2009). Three moored systems in Lunenburg Bay functioned very well from 2002 - 2007 (except during winter haul-out and some interruptions), providing real time data supported by nearly weekly sampling for ground-truth data. We also developed an interdisciplinary near-real-time forecasting capability. Data from the system continue to be used in modeling and other analyses (Laurent et al. 2009).

Redeployment of an optical mooring. Regrouping from the termination of our ocean observatory project, we refurbished and modified one of the Lunenburg buoys and established a strong collaboration with colleagues at the Bedford Institute of Oceanography to start a new program of observations, analysis, modeling and experimentation centered around the Bedford Basin Ocean Monitoring Buoy (BBOMB). The buoy was deployed at the site of more than forty years of observations, including more than 15 years of weekly sampling (with a few interruptions) for physical, chemical and biological properties, including flow cytometric characterization of the microbial assemblage complemented by HPLC pigment analysis. The time series, conducted by Dr.W.K.W. Li, is a tremendous resource that was complemented by continuous bio-optical assessment with weekly ground-truth sampling. The buoy operated from 3 October - 16 November, 2008, when it was severely damaged in a marine mishap and decommissioned. With funding from the Natural Sciences and Engineering Research Council of Canada and support from ONR, we worked with Satlantic to design and build a new buoy system suitable for year-round operation, even under icy conditions.

Retrieval of physiological information using measurements from conventional fluorometers. Adam Comeau completed a draft of his M.Sc. thesis, analyzing data from conventional fluorometers deployed on commonly used oceanographic profiling systems and novel systems (SeaHorse autonomous profiler and Satlantic's LOBO observatory) to retrieve estimates of $E_{f\ opt}$, the irradiance at which fluorescence yield of phytoplankton in a light gradient is maximal — a useful measure of photosynthetic physiology. His extended abstract (Comeau et al. 2008) was awarded Honorable Mention for student presentations at the Ocean Optics XIX meeting in Barga, Italy.

Sun-induced chlorophyll fluorescence. For years, we have studied natural variability in the yield of sun-induced chlorophyll fluorescence, trying to pursue a technically rigorous, quantitative and conservative approach, firmly based in the established literature. John Cullen used this framework in a critique of a study that was much more expansive in the interpretation of its results (Cullen 2009a).

Interdisciplinary modeling. Numerical modeling of ocean processes continues to be centrally important to our research. Both Arnaud Laurent (modeling Lunenburg Bay; Laurent et al. 2009) and Diego Ibarra (mussel farms in Ship Harbour; Ibarra et al., 2009) worked with our colleague Katja Fennel to implement the ROMS modeling system in their research.

Ocean fertilization. The controversy over fertilization of the ocean for climate change mitigation has persisted for 20 years. Cullen discussed the issues during invited plenary addresses at the ASLO (Advancing the Science of Limnology and Oceanography) Aquatic Sciences Meeting in Nice, France, and at the Canadian Meteorological and Oceanographic Society (CMOS) Congress in Halifax. With Aaron Strong and Sallie W. Chisholm of MIT, he contributed to a critical review of the history of ocean fertilization in the peer-reviewed magazine, *Oceanography*. Also (with Charles Miller from Oregon State University), they published an opinion piece in *Nature*. Both pieces supported the same conclusion: it is time to stop considering ocean fertilization as an option for geo-engineering. This is unlikely to end the controversy, but it will focus the debate.

RESULTS

As this report is written, the Bedford Basin Ocean Monitoring Buoy is being deployed and will provide optical, physical, meteorological and chemical measurements every half hour, throughout the year. The new project represents the application of years of research and hands-on experience with ocean observatories. The surface sensors onboard include hyperspectral downwelling irradiance and upwelling radiance, and a meteorological station. At depth, the buoy is equipped with three sensor chains that measure conductivity, temperature and depth, multispectral downwelling irradiance, chlorophyll and CDOM fluorescence, particulate backscatter, multispectral total absorption and attenuation, oxygen and nitrate. These measurements will be transmitted back to Dalhousie every half hour, where they will be subject to quality assurance and control, processing and display on our web interface in near-real time. The web component of the project is vital, and we intend that our data products will be accessible to both the scientific community and general public alike through easily interpretable data visualization interfaces such as Google Earth (Fig. 1a).

Dalhousie and Bedford Institute of Oceanography (BIO) field teams visit the buoy site weekly to collect discrete water samples and full water column profiles of physical and apparent and inherent optical properties. The weekly AOP measurements collected by Dalhousie forms a significant and important part of a data set currently being used by Dr. Edward Horne (BIO) in a project to investigate the use of MERIS imagery in coastal waters (Fig. 1b). We have also recently been approached by NRL as potential providers of calibration and validation data for the recently launched Hyperspectral Imager for the Coastal Ocean (HICO) sensor on the International Space Station. It is intended that data from the buoy and weekly sampling will be used extensively in the development of inversion algorithms for complex coastal waters such as Bedford Basin, including assessments of the factors that lead to the failure of conventional approaches; atmospheric correction algorithms (Horne *et al*., BIO); investigation of optical approaches to detect and assess harmful algal blooms; and investigation of the physical and ecological contributions to variability in the quantum yield of sun-induced chlorophyll fluorescence.

IMPACT/APPLICATIONS

Coastal observatories. After nearly two years "out of the water" with our ocean observatory systems, we are initiating a new program of ocean monitoring and analysis — in collaboration with the Bedford Institute of Oceanography — that will incorporate state-of-the-art optical observations with one of the most comprehensive time-series studies of marine microbial ecology, along with remote sensing (MERIS) and a potent real-time, web-based interface. We hope that the BBOMB will eventually form a major component in an integrated research program involving several federal and provincial partners that will encompass remote sensing and interdisciplinary observations from the near-real time buoy, discrete sampling, and glider measurements — ultimately assimilated by biophysical models of the region.

Ocean fertilization. After twenty years, the controversy over ocean fertilization for climate mitigation has not gone away. It is hoped that the critical review of the history of ocean fertilization in the peer-reviewed magazine, *Oceanography*, and a related piece in *Nature*, will help during international efforts to assess and perhaps resolve outstanding issues.

Fluorescence. We continue to develop a quantitative and comprehensive framework for interpreting measurements of chlorophyll fluorescence with the expectation that research using interpretations of chlorophyll fluorescence will expand. With the development of new fluorometers for ocean gliders and newly published research on physiological interpretations of fluorescence as measured from space, there is a need for quantitative, experimentally based interpretations, and we feel that our research will contribute to that.

New directions in interdisciplinary oceanography. Cullen's contribution to the proceedings of the U.S. Ocean Studies Board / National Research Council workshop, "Oceanography in 2025", was published by the National Academies Press. The essay, "Integrated Oceanography in 2025", is presented first among the fifty reports from a broad range of oceanographers; it proposes that oceanography should become part of a profoundly crosscutting Global Environmental Portfolio that must be developed if humanity is to meet the challenges of climate change and increasing human impacts on the planet. Cullen also contributed to another essay on important scales of variability in the ocean (Rudnick et al. 2009). Further, he has been working with colleagues on the Oceans Task Team of the Canadian Institute for Advanced Research (CIFAR), conducting a series of highly interdisciplinary workshops, assembling researchers from around the world to discuss the next big questions in ocean science. The next workshop, "Humans Transforming the Ocean Nitrogen-Cycle: From 1950 to 2050 to 2150", promises to be exciting.

TRANSITIONS

Slides from Cullen's plenary addresses on ocean fertilization were transmitted to Dr. Julie Morris, Director of NSF's Division of Ocean Sciences, and Ms. Helen Joseph, Director of the Oceanography and Climate Branch of the Canadian Hydrographic Service, at their request. Cullen then served on a

Department of Fisheries and Ocean national peer review panel on ocean fertilization in preparation for a meeting of the London Convention.

RELATED PROJECTS

1) NSERC/Satlantic Industrial Research Chair: this partnership is the focus of support for Cullen's research activities. Funding for complementary projects, such as this ONR program, are highly leveraged by the research partnership and associated grants. This project (as well as NSERC Research Tools and Instruments) provides much of the support for the Bedford Basin Ocean Monitoring Buoy program.

2) There are intellectual connections with the with Radiance in a Dynamic Ocean program (Lewis, PI).

3) A research project funded by Cellana BV is aimed at screening strains of microalgae for their potential to produce next-generation biofuels and protein. The project provided funds for new equipment (including an excellent spectrophotometer) and renovations, and leverages fundamental research on fluorescence.

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Laurent A., A.F. Vézina, K. Fennel and J.J. Cullen. Modelling the biological effects of summer upwelling events in Lunenburg Bay, Canada. Canadian Meteorological and Oceanographic Society Congress, Halifax: June 2009.

PUBLICATIONS

The following manuscripts resulted in full or in part from this contract:

Cullen, J.J. 2009a. Interactive comment on "Satellite-detected fluorescence reveals global physiology of ocean phytoplankton" by M. J. Behrenfeld et al. Biogeosciences Discuss., 5, S2646–S2655, 2009.
Cullen, J.J., 2009b. Integrated oceanography in 2025. pp. 3-5 in: "Oceanography in 2025: Proceedings of a Workshop." National Academies Press. http://www.nap.edu/catalog/12627.html

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Wang L., R. M. Moore, J. J. Cullen (2009), Methyl iodide in the NW Atlantic: Spatial and seasonal variation, J. Geophys. Res., 114, C07007, doi:10.1029/2007JC004626. [refereed]

HONORS

John Cullen, Dalhousie University, was elected Councillor of the Oceanography Society.

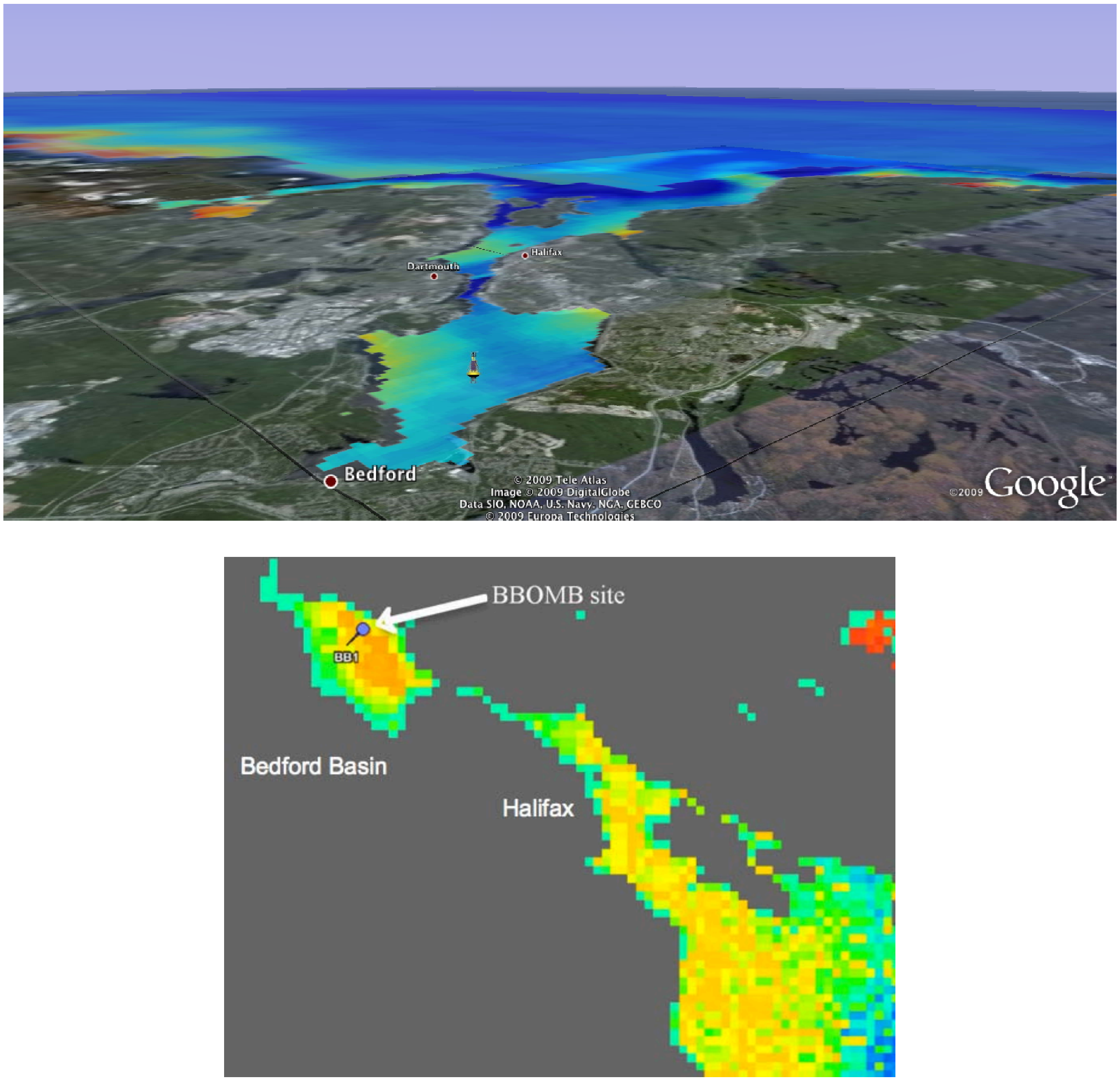

Figure 1. Upper panel: Google Earth overlay of a synthetic chlorophyll a data set in Bedford Basin and Halifax Harbour – one form of data visualization that will be used on the Bedford Basin Ocean Monitoring Buoy (BBOMB) website. Lower panel: MERIS (European Space Agency) Algal Pigment Index II chlorophyll a concentration in Bedford Basin in September 2009. MERIS resolution of 300 m provides several uncontaminated pixels in the Basin.

[Graph: In the upper panel, an image from Google Earth at an oblique angle shows Bedford Basin and Halifax Harbor, with the Scotian Shelf in the background. The BBOMB buoy is shown, as is a representation of estimated chlorophyll as it might be retrieved from remote sensing. The lower panel shows a satellite image of chlorophyll in Bedford Basin and Halifax Harbour, including many dozens of pixels uncontaminated by land in this port.]